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ON THE SENSITIVITY OF BRIDGE SEISMIC RESPONSE WITH LOCAL SOIL AMPLIFICATION

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SUMMARY

The paper presents a numerical sensitivity study of the local site effects on structural response. Following a recently developed model of spatial coherency and a concept of a simple site coefficient the local site effects are modelled as filtrations of excitation processes with a frequency shift. An analysis of a bridge response with supports founded on different soils is carried out. The joint effects of dynamic response and pseudostatic motion are considered. Two types of response are analysed: longitudinal and transverse. The differences between dynamic displacements and force responses are pointed out. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: spatial seismic response; soil amplification; bridges

INTRODUCTION

Spatial seismic variability can be attributed to three main sources: (1) complexity of seismic source, (2) finite velocity of wave propagation, (3) geological and geometrical heterogeneities of the ground. The first source of spatial variability depends on the site–epicenter distance, and can be important for near-field earthquakes. The second affects structural response and depends directly on support distances, since there is a signal delay with increasing distance. Finally, the third source of spatial seismic variability leads to complex problems of wave diffractions and interference,[1,2] as well as to local soil amplifications. Unlike the first two sources, which manifest their structural effects with increasing support distances, the local soil effects can be important even for relatively short support distances. These soil amplification effects are still not sufficiently understood although, for example, they are believed to have contributed substantially to the collapse of the Cypress Street Viaduct in the 1989 Loma Prieta earthquake.[3]

Site effects have been studied by several authors.[4–7] These studies concentrate on sophisticated seismological modelling of this complex phenomenon at a particular geological location.

The purpose of this paper is to perform random vibration, sensitivity analysis of the structural response to variations in the local spectral amplification of the supports of a bridge structure. For this purpose a simple model, still capturing the essential effects of soil amplification, has been chosen. This is the spatial coherency model proposed by Der Kiureghian[8] using the Kanai–Tajimi filter, as modified by Ruiz and Penzien.[9] The model is applied to a bridge structure excited in the longitudinal and the transverse directions.

MODELLING SPATIAL SEISMIC EFFECTS

Consider the complex coherency function

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$$\gamma_{jk}(\omega) = \frac{S_{jk}(\omega)}{\sqrt{S_{jj}(\omega)\, S_{kk}(\omega)}} \tag{1}$$

defined for two accelerations $\ddot{u}_j(t)$ and $\ddot{u}_k(t)$ at stations j and k separated by some spatial distance, where $S_{jj}(\omega)$, $S_{kk}(\omega)$ and $S_{jk}(\omega)$ denote point spectral densities of the accelerations and their co-spectrum, respectively. In a recent paper Der Kiureghian[8] proposed a general composite model of spatial seismic coherency in the following form:

$$\gamma_{jk}(\omega) = \gamma_{jk}^{(i)}(\omega)\, \gamma_{jk}^{(w)}(\omega)\, \gamma_{jk}^{(s)}(\omega) = \gamma_{jk}^{(i)}(\omega) \exp[\imath(\Theta_{jk}^{(w)}(\omega) + \Theta_{jk}^{(s)}(\omega))] \tag{2}$$

where $\gamma_{jk}^{(i)}(\omega)$ is derived from the loss of coherency (incoherence) between stations j and k, $\gamma_{jk}^{(w)}(\omega)$ is a complex coherency resulting from phase delay in the wave propagation, $\gamma_{jk}^{(s)}(\omega)$ represents local site effects and $\imath = (-1)^{1/2}$. Note that the loss of coherency is represented by a real function whereas wave passage and site effects result in the phase changes $\Theta_{jk}^{(w)}(\omega)$ and $\Theta_{jk}^{(s)}(\omega)$ of the complex coherency.

Consider now a situation in which all the spatial effects are disregarded except site effects. Following Der Kiureghian[8] site effects are described by the local soil frequency response functions $H_j(\omega)$ and $H_k(\omega)$ representing filtration through soil layers between bedrock and surface for stations j and k, respectively. This leads to relations between the bedrock cross- and auto-spectral densities $S_{jk}^{(b)}(\omega)$, $S_{jj}^{(b)}(\omega)$, and the surface spectral densities $S_{jk}^{(r)}(\omega)$, $S_{jj}^{(r)}(\omega)$, in the following form:

$$S_{jk}^{(r)}(\omega) = H_j(\omega)\, H_k^*(\omega) S_{jk}^{(b)}(\omega), \quad S_{jj}^{(r)}(\omega) = |H_j(\omega)|^2 \; S_{jj}^{(b)}(\omega), \tag{3a,b}$$

in which H_k^* is the complex conjugate of H_k. When only site effects are considered the complex coherency function (equation (2)) becomes

$$\gamma_{jk}(\omega) = \exp[\imath\, \Theta_{jk}^{(s)}(\omega)] \quad \text{with} \quad \Theta_{jk}^{(s)}(\omega) = \tan^{-1} \frac{\mathrm{Im}[H_j(\omega)\, H_k^*(\omega)]}{\mathrm{Re}[H_j(\omega)\, H_k^*(\omega)]} \tag{4a,b}$$

Consider now the surface spectral density function as given by equation (3a), in which

$$H_j(\omega) = \frac{\omega_j^2 + 2\imath\xi_j\omega_j\omega}{\omega_j^2 - \omega^2 + 2\imath\xi_j\omega_j\omega} \tag{5}$$

represents the soil filter at site j, and the bedrock spectrum $S_{jk}^{(b)}(\omega)$ denoted here for brevity as $S(\omega)$, is given by

$$S(\omega) = \frac{\omega^4}{(\omega_b^2 - \omega^2)^2 + 4\xi_b^2\omega_b^2\omega^2} S_0 \tag{6}$$

The auto-spectrum (3b) takes the familiar form of the filtered Kanai–Tajimi function with modification[9]

$$S_{jj}^{(r)}(\omega) = |H_j(\omega)|^2\, S(\omega) = \frac{\omega_j^4 + 4\xi_j^2\omega_j^2\omega^2}{(\omega_j^2 - \omega^2) + 4\xi_j^2\omega_j^2\omega^2}\, \frac{\omega^4}{(\omega_b^2 - \omega^2)^2 + 4\xi_b^2\omega_b^2\omega^2} S_0 \tag{7}$$

in which S_0 is an intensity multiplier, the parameters ω_b and ξ_b are constants: $\omega_b = 1{\cdot}636$, $\xi_b = 0{\cdot}619$, whereas the dominant frequency ω_j and damping ratio ξ_j are chosen so as to model the actual soil filtration. Although other, more sophisticated models of soil filtration may be used[6,7] there is a general agreement[6] that as the site becomes 'stiffer' the surface spectral density becomes broader with a shift in the dominant frequencies. Assuming for firm ('stiff') ground $\omega_j = 6\pi$ rad/s and $\xi_j = 0{\cdot}6$, and for very 'soft' soil $\omega_j = \pi$ rad/s and $\xi_j = 0{\cdot}1$ leads to following relationships:

$$\omega_j = g_s\pi \quad \xi_j = g_s 0{\cdot}1 \tag{8}$$

with $1 < g_s < 6$, where g_s is a site coefficient since it measures the filtration effects of soil. In Figure 1 the auto-spectrum (equation (9)) is plotted for $g_s = 1, 2, \ldots, 6$. It should be pointed out that the adjectives 'stiff' or 'soft' are applied here in the absence of more precise definitions describing soil filtration. It is obvious that changes in the site coefficient g_s also imply changes in soil compliance. However, addressing these problems would require a soil-structure interaction analysis which exceeds the scope of this paper.

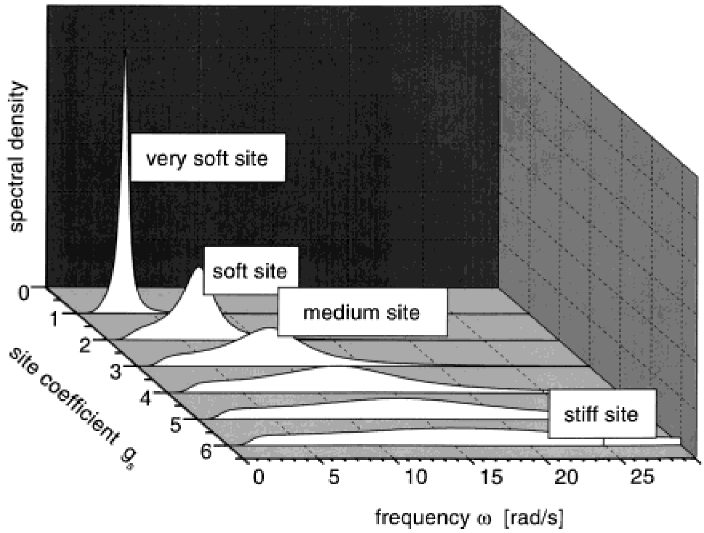

Figure 1. Modified Kanai–Tajimi spectral densities with site coefficient g_s varying from 1 to 6

RESPONSE OF A BRIDGE STRUCTURE

Consider the bridge structure shown schematically in Figure 2. It is a reinforced concrete bridge with a box type deck (area 3·71 m^2, moments of inertia: 15·08 m^4 for bending in the horizontal plane and 3·48 m^4 for bending in the vertical plane), and piers of circular cross-sections (cross-sectional area 2·01 m^2, moment of inertia 0·322 m^4). The first five natural frequencies of the bridge are: 10·13 rad/s — longitudinal; 11·26, 17·10 rad/s — transverse; 22·28, 31·35 rad/s — vertical. The bridge is modelled as a multi-degree-of- freedom structure. The equation of motion of the system under multi-support excitations takes the following form:[10]

$$\mathbf{M}\ddot{\mathbf{q}}^{t} + \mathbf{C}\dot{\mathbf{q}}^{t} + \mathbf{K}\mathbf{q}^{t} = \begin{bmatrix} \mathbf{M}_{ss} & \mathbf{M}_{sg} \\ \mathbf{M}_{gs} & \mathbf{M}_{gg} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{q}}_s^{t} \\ \ddot{\mathbf{u}} \end{Bmatrix} + \begin{bmatrix} \mathbf{C}_{ss} & \mathbf{C}_{sg} \\ \mathbf{C}_{gs} & \mathbf{C}_{gg} \end{bmatrix} \begin{Bmatrix} \dot{\mathbf{q}}_s^{t} \\ \dot{\mathbf{u}} \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_{ss} & \mathbf{K}_{sg} \\ \mathbf{K}_{gs} & \mathbf{K}_{gg} \end{bmatrix} \begin{Bmatrix} \mathbf{q}_s^{t} \\ \mathbf{u} \end{Bmatrix} = \begin{Bmatrix} \mathbf{0} \\ \mathbf{R}_g \end{Bmatrix} \tag{9}$$

where $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$, are mass, damping and stiffness matrices, respectively, $\mathbf{q}^t = [q_1, q_2, \ldots, q_{n_s}, u_1, u_2, \ldots, u_{n_g}]^T$, is a total displacement vector with $n_s + n_g$ elements (with reference to fixed coordinates), $\mathbf{q}_s$ and $\mathbf{u}$ are subvectors containing, respectively, structural degrees of freedom and support displacements, $\mathbf{R}_g$ is the vector of reaction forces. Noting that the total response $\mathbf{q}^t = \mathbf{q} + \mathbf{q}^p$ consists of dynamic ($\mathbf{q}$) and pseudostatic ($\mathbf{q}^p$) displacements, it can be shown that for small or stiffness-proportional damping equation (9) is equivalent to

$$\mathbf{M}_{ss}\ddot{\mathbf{q}} + \mathbf{C}_{ss}\dot{\mathbf{q}} + \mathbf{K}_{ss}\mathbf{q} = (\mathbf{M}_{ss}\mathbf{K}_{ss}^{-1}\mathbf{K}_{sg} - \mathbf{M}_{sg})\ddot{\mathbf{u}} \tag{10}$$

Assuming $\ddot{\mathbf{u}}$ to be a stationary vector random process with co-spectral densities $S_{jr}(\omega), j, r = 1, 2, \ldots, n_g$, and applying the method of mode superposition result in the mean-square solution of equation (10) in the following form:[11]

$$\sigma_{q_k}^2 = \sum_{i=1}^{n_s} \sum_{p=1}^{n_s} W_{ki} W_{kp} \int_{-\infty}^{\infty} H_i(\omega) H_p^*(\omega) \sum_{j=1}^{n_g} \sum_{r=1}^{n_g} G_{ij} G_{pr} S_{jr}(\omega)\, d\omega \tag{11}$$

in which W_{ki}, W_{kp} are elements of eigenvectors $\mathbf{w}_i$ and $\mathbf{w}_p$, respectively, $H_i(\omega) = (\omega_i^2 - \omega^2 + 2\imath\xi_i\omega_i\omega)^{-1}$ is the modal frequency response function, ω_i, ξ_i are, respectively, the natural frequencies and modal damping ratios, and G_{ij} are elements of following matrix $\mathbf{G}$:

$$\mathbf{G} = \mathrm{diag}(1/m_i)\mathbf{W}^T(\mathbf{M}_{ss}\mathbf{K}_{ss}^{-1}\mathbf{K}_{sg} - \mathbf{M}_{sg}) \tag{12}$$

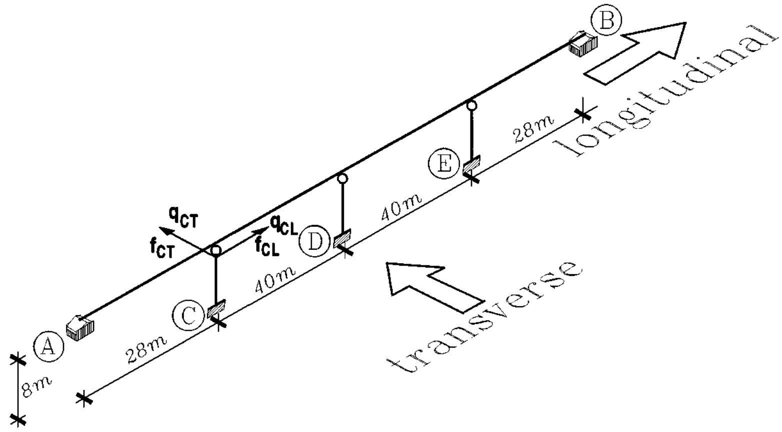

Figure 2. Bridge structure under longitudinal and transverse excitations

with diag($1/m_i$) denoting a diagonal matrix with elements $1/m_i$, $\mathbf{W}$ the eigenmatrix and $m_i = \mathbf{w}_i^T \mathbf{M}_{ss} \mathbf{w}_i$. Similarly, the rms pseudostatic displacements and rms internal forces can be calculated directly from the displacements or using FEM formulas. For the bridge in Figure 2 the shear forces in the piers C, D, E can be calculated directly from support displacements. For example, the transverse force in pier C $f_{CT} = (q_{CT} + q^p_{CT} - u_{CT})3EI/\ell^3$, where q_{CT} and q^p_{CT} are dynamic and pseudostatic displacements, u_{CT} = transverse displacements of support C, EI = flexural stiffness and ℓ height of the pier.

The effect of local soil amplification on the bridge structure is analysed for the longitudinal and transverse directions (Figure 2).

Numerical analysis is performed with the assumption that one of the supports is founded on soft soil while the others are on firm ground. In Figure 3 the rms nodal displacements (a,b) and shear forces (c,d) are, respectively, presented for the longitudinal excitation (a,c) and the transverse direction (b,d), with soft soil under one of the supports A, B, C, D or E. The results are normalized with respect to uniform excitations, therefore all the plots are equal to 1 for $g_s = 6$ (the same firm ground for all the supports). It can be seen from Figure 3(a) that, as expected, the displacements along the bridge (q_{CL}) do not depend on the location of the soft soil support. On the other hand, the shear force f_{CL} (Figure 3(c)) depends more clearly on the soft soil location. In both cases there is a slight amplification with decreasing g_s and then a dip near $g_s \cong 2$. For low g_s values the force (but not the displacement) increases rapidly with decreasing g_s, giving substantial amplification. In Figure 3(b) and (d) these effects are shown for vibrations in the transverse direction. In this case a similar diversity of results can be observed for both displacements and forces. It is interesting to note that the strongest local soil effects are on forces and displacements at the support where the soft soil is located. This holds to a similar extent for all the plots except Figure 3(b), where the soft soil at the support D gives the lowest response. Some locations of the soft soil affect the results very little (e.g. E in Figure 3(b) and B in Figure 3(d)).

FINAL REMARKS AND CONCLUSIONS

Results of a limited parametric study on the effect of local soil amplification on the seismic response of a bridge structure are reported. For this purpose a simple 'site' coefficient g_s measuring bandwidth and frequency shift of soft soil has been introduced. The analysis is limited to non-uniform soil filtration effects.

Two main phenomena govern the behaviour of this structure: (1) Resonance amplification when the soil frequency is close to one of the important natural frequencies of the structure. (2) Pseudostatic amplification, which can be observed for the force response at low values of the coefficient g_s for one of the supports.

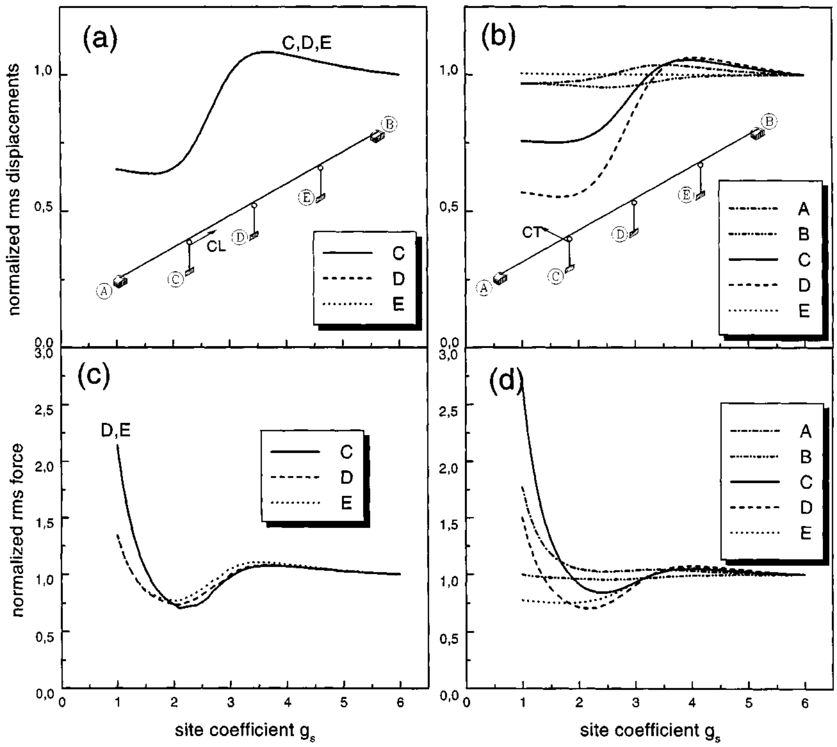

Figure 3. Normalized rms response (displacements q_{CL}-(a) and force response f_{CL}-(c)), for excitations along the structure as well as for transverse excitations (q_{CT}-(b) and f_{CT}-(d)) vs. site coefficient g_s. Soft local soil assumed at the sites A, B, C, D or E and for the rest firm ground

Generally, forces are affected more than dynamic displacements. Observing the bridge response as displayed in Figure 3 it can be seen that when the local site coefficient g_s decreases from 6 (uniform excitations) to 1 (substantial local amplification), there is first a slight amplification which is followed by a dip and then again a substantial amplification. The strongest local site amplification effects can be observed for the forces and displacements of the piers where the soft soil is located.

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